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INVESTIGATION OF CONDENSATION/CLUSTERING EFFECTS ON RAYLEIGH SCATTERING MEASUREMENTS IN A HYPERSONIC WIND TUNNEL

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ABSTRACT

Rayleigh scattering, a nonintrusive measurement technique for the measurement of density in a hypersonic wind tunnel, is currently under investigation at Wright Laboratory's Mach 6 wind tunnel. Several adverse effects, i.e. extraneous scatter off walls and windows, hinder Rayleigh scattering measurements. Condensation and clustering of flow constituents also present formidable obstacles to overcome. Overcoming some of these difficulties, measurements have been achieved while the Mach 6 test section was pumped down to a vacuum, as well as for actual tunnel operation for various stagnation pressures at fixed stagnation temperatures. Stagnation pressures ranged from 0.69MPa to 6.9MPa at fixed stagnation temperatures of 511, 556 and 611K. Rayleigh scatter results show signal levels much higher than expected for molecular scattering in the wind tunnel. Even with higher-than-expected signals, scattering measurements have been made in the flowfield of a 8-degree half-angle blunt nose cone with a nose radius of 1.5 cm.

INTRODUCTION

Extraneous scattering off tunnel walls and windows and condensation effects have always caused problems with using the Rayleigh scattering technique in hypersonic wind tunnels. Eliminating surface scatter background noise overcomes only one of the adverse effects troubling the Rayleigh scatter technique. Condensation and clustering of the flow constituents has been found to hamper Rayleigh scatter measurements[1,2]. The condensation of air in hypersonic wind tunnels takes place at relatively low supersaturation ratios. This is possibly condensation taking place onto nuclei of water and/or carbon dioxide, which exist in the air as minor components, and which condense well before the saturation of nitrogen or oxygen is reached. The condensation of the water and/or carbon dioxide does not seriously affect the stream properties because of the small percentage in which they exist. However, a large number of nuclei are formed in the condensation of these minor components, which then act as nuclei for oxygen and nitrogen condensation at low degrees of supersaturation of these principal components. Throughout the past, a lot of research regarding condensation in supercooled hypersonic flow has been performed[3,4,5,6]. Condensation/clustering biases will be discussed in a later section.

EQUIPMENT AND FACILITY DISCUSSION

The Rayleigh scattering measurement system located at Wright Laboratory's Mach 6 wind tunnel is shown in figures 1 and 2. A standard Nd:YAG pulsed laser, producing a frequency doubled 532nm beam, pumps two oscillator-amplifier, tunable dye lasers. However, only one dye laser is required for the Rayleigh scatter system so the output from one of the dye lasers is blocked. The unblocked dye laser is tuned such that the wavelength of the exit beam is 613nm. This exit beam is then frequency doubled using a BBO doubling crystal resulting in a beam with a wavelength of ~306.5nm. As a result of the doubling process and optical set-up the red beam, 613nm, and the UV beam, 306.5nm, are collinear.

The collinear beams pass through a gas reference cell containing a gas at a known pressure and temperature. The gas in the reference cell is comparable to the gas being measured in the wind tunnel. For this experiment the gas is standard air. The reference cell provides a means of eliminating pulse-to-pulse laser power fluctuations. Two photomultiplier tubes (PMT), one for the red beam the other for the UV beam, are mounted within the reference cell. The PMTs collect scattered light; converting it into a signals, referred to as "reference" signals. The reference signals are used to normalize the actual signals, referred to as "sample" signals, in the wind tunnel's test section from small variations in the relative laser pulse energy.

After exiting the reference cell the laser beams are directed into the test section through a fused-silica window. Two 90-degree turning prisms steer the beams such that they enter the window on one side of the test section and strike the wall on the other side.

A light collection system consisting of a 30cm focal length planoconvex lens, bandpass filters and two PMTs, red and UV respectively, is mounted on a three-dimensional traverse outside the test section. The angle of observation is perpendicular to the direction of the incident light. The reference and sample signals are collected by a data acquisition computer system. The acquisition computer system consists of gated integrators, A/D converter and a 286 IBM-compatible computer.

The Wright Laboratory's Mach 6 wind tunnel, see figure 3, is a blowdown tunnel which uses dried, compressed air. The air is heated to 500-611K by a heater bed of stainless steel balls prior to entering the stagnation chamber. The tunnel has an axis-symmetric, 31.36cm diameter nozzle contoured to produce an uniform flow which has a calibrated centerline Mach number of 5.76. The tunnel was operated over a range of stagnation pressures, 0.69MPa - 6.9MPa in increments of 0.69MPa, at fixed stagnation temperatures, 511, 556 and 611K. For stagnation pressures less than 4.14MPa the air exhausted from the tunnel is directed into a 2,831 m^3 vacuum sphere, see figure 4; otherwise the tunnel is exhausted to atmosphere.

RESULTS

The main assumption of the Rayleigh scattering measurement system at Wright Laboratory is that Rayleigh coefficients are proportional to air density. In other words, there is a linear relationship between the air density and the intensity of scattered light. With this understanding, intensity measurements were taken in a no flow situation at atmospheric and very low pressure conditions; pressures and temperatures were obtained from static probes within the test section. Now, since intensities at two known density conditions were obtained, a line can be drawn which shows the relation between density and intensity. By using this relation the surface scatter background noise can be determined and eliminated,

$$slope = M = \frac{(I_2 - I_1)}{(\rho_2 - \rho_1)} \tag{1}$$

$$background\ scatter = b = I_1 - M*\rho_1 \tag{2}$$

It may be noted that the UV light makes for better Rayleigh scatter measurements than the red light, which follows the theory as expected.

To better see the linear relation between density and intensity of scattered light the test section was slowly pumped down to a very low pressure. Rayleigh scattering measurements were performed during the evacuation process, tracking the density of the air in the test section to its lower limit of .019 kg/m^3. These tracking measurements are shown in figure 5.

Since the Rayleigh scattering measurement system appeared to track the tunnel density readings well, the test section was quickly evacuated to a low pressure. When the test section is quickly evacuated the temperature decreases both suddenly and drastically. Water vapor present in the air spontaneously condenses and fills the test section with condensation particles. Condensed water droplets cause both PMTs, red and UV wavelengths respectively, to reach saturated levels, as seen in figure 6. When the tunnel is started and operating at hypersonic flow conditions, neither PMT reach saturation conditions. This observation, along with studies of intensity measurements obtained through a polarization filter rotated through various angles 0, 45 and 90 degrees, lead to the belief that although condensation of carbon dioxide and possible clustering of oxygen and nitrogen occur, large dust particles are not present during tunnel operation.

Although large dust particles apparently are absent from the flow during tunnel operation, higher-than-expected intensity signals were acquired when the tunnel was operating at the aforementioned conditions. As shown in figure 7, the intensity signals diverge from the expected measurements quite dramatically for the lower stagnation temperature. Even at the lowest stagnation temperature, 511K, and the highest stagnation pressure, 6.9MPa, condensation of the principal components of air, nitrogen and oxygen, should not occur. However, carbon dioxide, which exists in air as a minor component, condenses well before the saturation of nitrogen or oxygen, see figure 8. The condensation of carbon dioxide does not seriously affect the stream properties because of the small percentage in which they exist. However, a large number of nuclei are formed in the condensation of carbon dioxide, which then may act as nuclei for oxygen and nitrogen condensation at low degrees of supersaturation of these principal components. Even if the condensed carbon dioxide does not cause the primary constituents of air to condense the carbon dioxide condensation particles formed will still foul Rayleigh scattering measurements.

Under the belief that the condensation particles formed by the expansion of the gas from the stagnation chamber are small and may possibly evaporate traveling through a strong shockwave measurements were made on a 8-degree half-angle blunt nose cone shown in figure 8. Measurements were taken on a line perpendicular to the surface of the cone at 12.7 cm back from the tip of the nose. These Rayleigh scattering measurements were compared to computational fluid dynamics results. Close to the surface of the cone the measurements agree while further off the surface and into the freestream it is apparent that the Rayleigh scattering measurements are quite higher-than-expected. Although the quantitative results disagree, it is reassuring to see that qualitatively the two techniques, Rayleigh scattering and computational fluid dynamics, appear similar.

CONCLUSIONS

Extraneous surface scatter background noise and scatter off condensation particles create difficulties in using Rayleigh scatter as a measurement technique in hypersonic flows. Fortunately, the surface scatter background noise has been eliminated by taking scattered intensity readings at two known density conditions, obtaining the linear relation between density and scattered intensity and calculating the level of extraneous background scatter. Condensation particle effects also have been addressed. Since results of the blunt nose cone measurements are qualitatively similar to the computational fluid dynamics results, research into the kinetics of condensation will be pursued.

ACKNOWLEDGEMENTS

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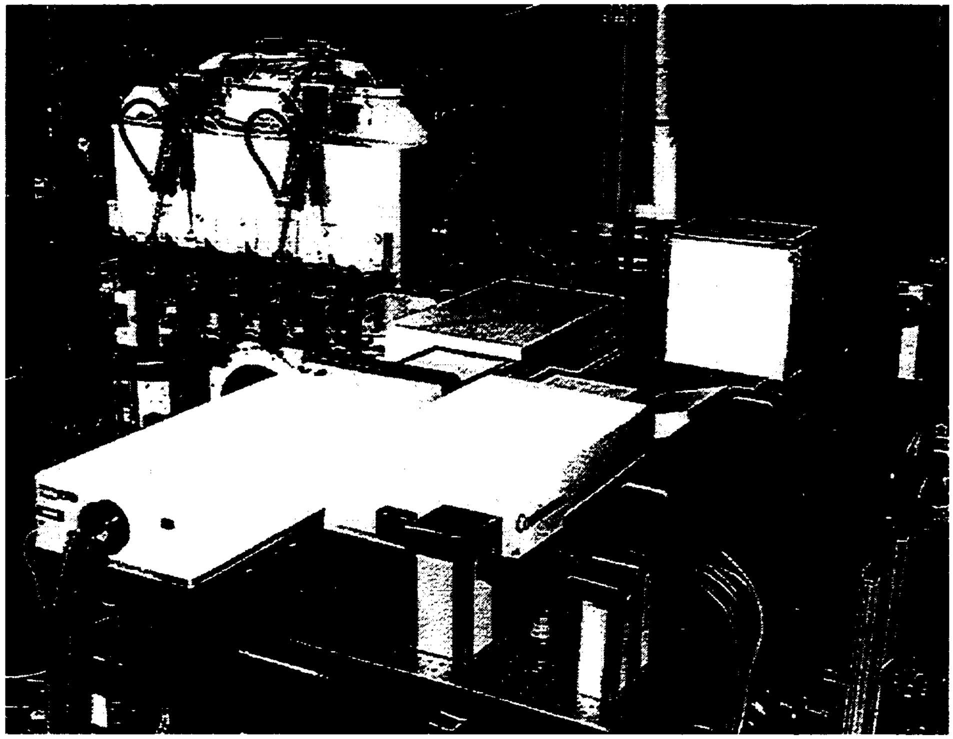

Fig. 1 Rayleigh scattering measurement system.

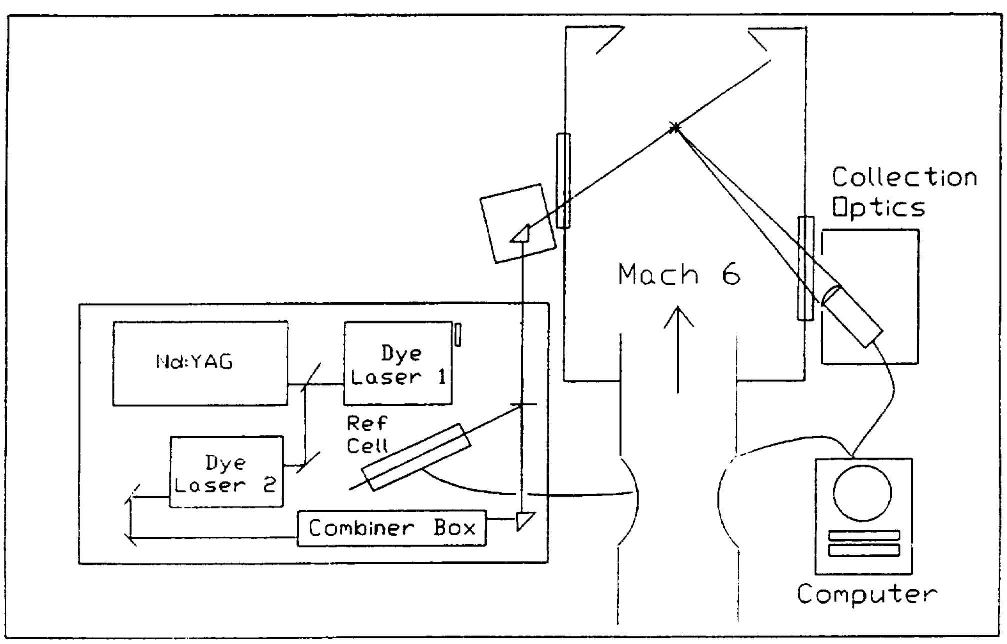

Fig. 2 Schematic of the Rayleigh scattering measurement system.

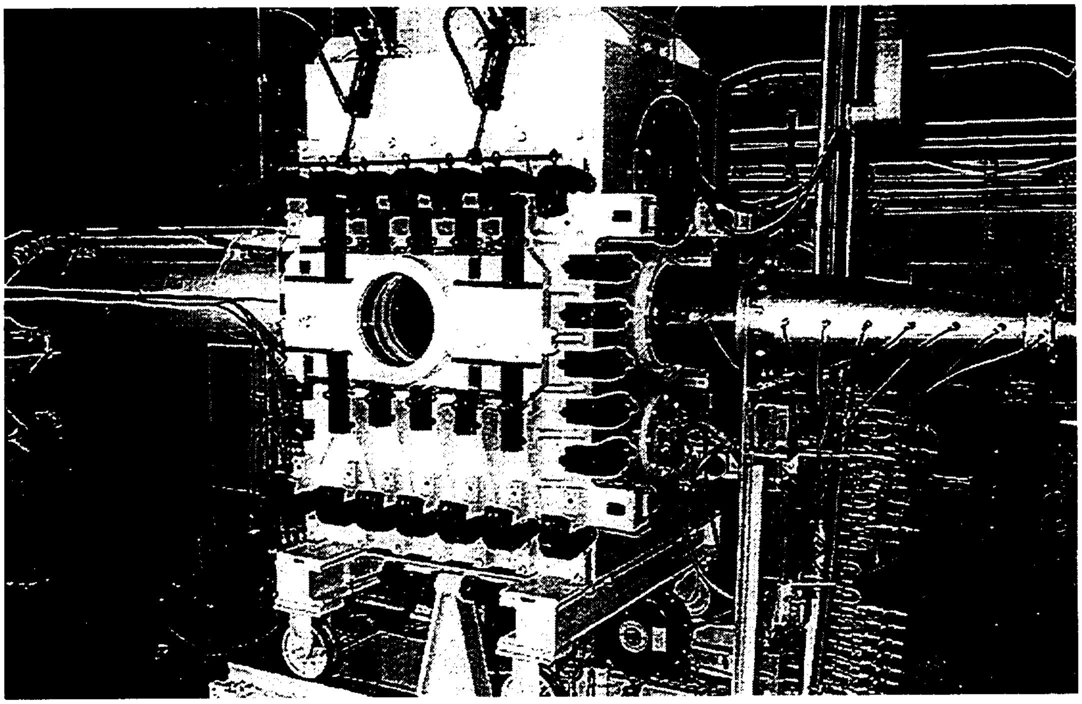

Fig. 3 Wright Laboratory's Mach 6 wind tunnel.

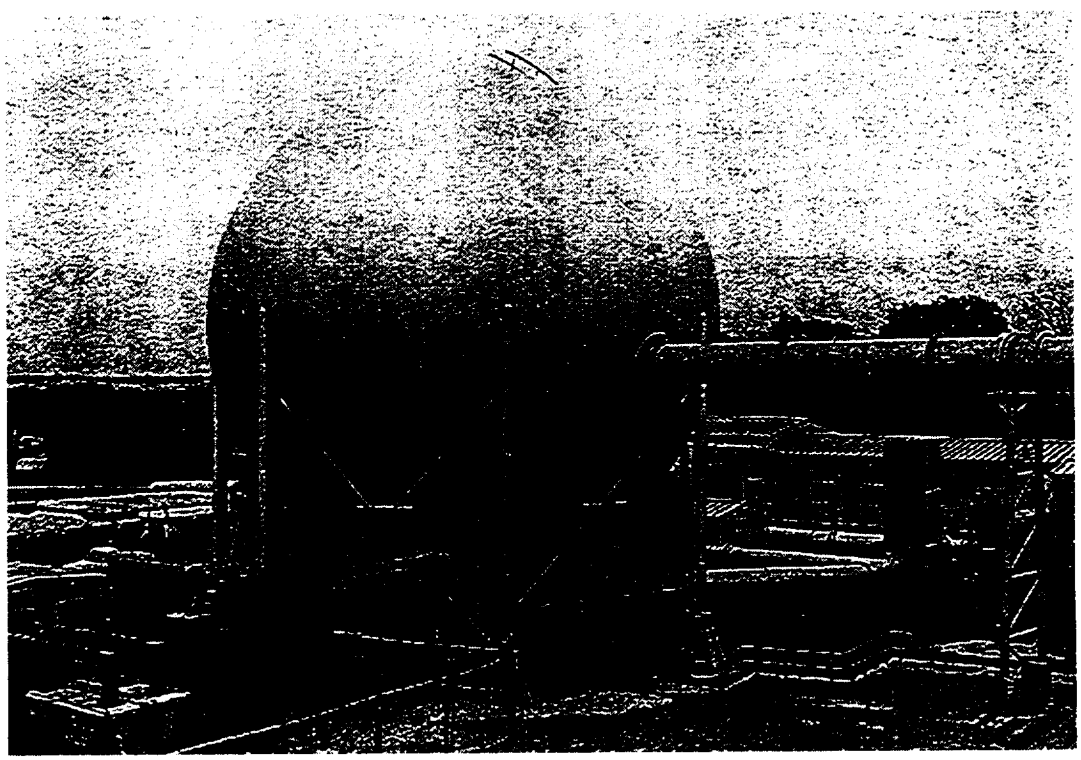

Fig. 4 Facility vacuum sphere.

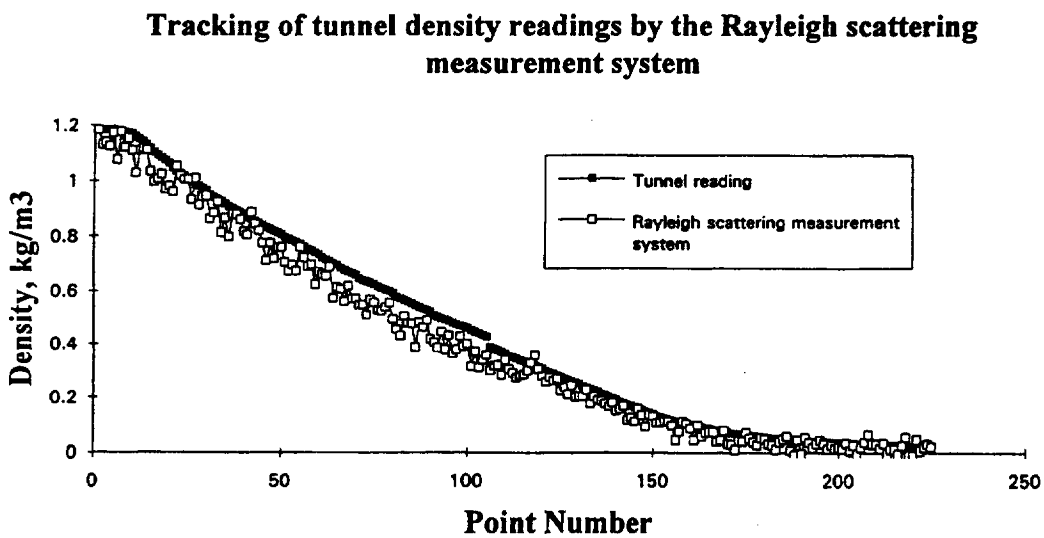

Fig. 5 Density tracking measurements.

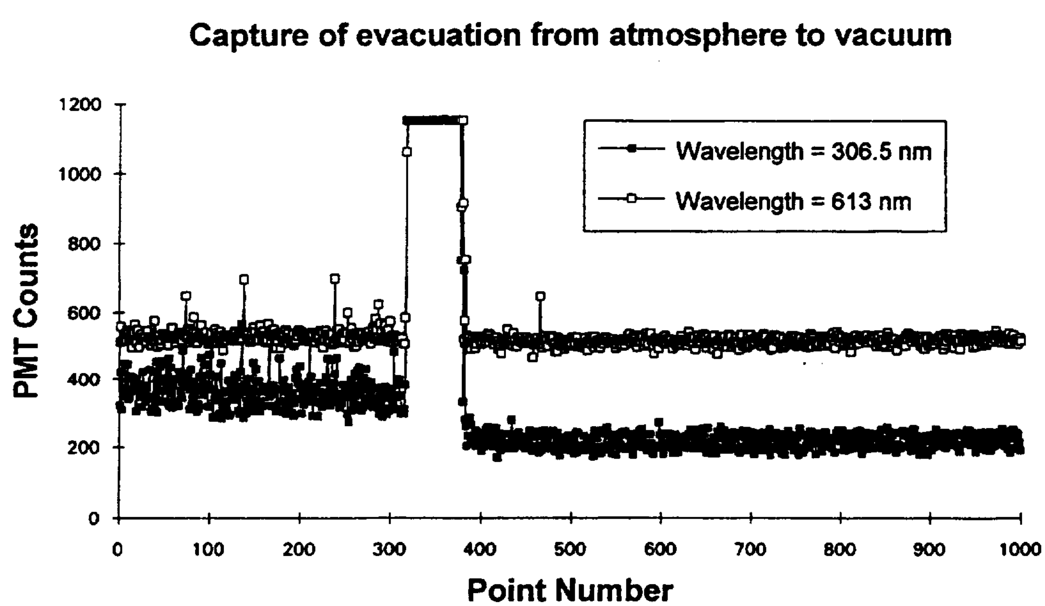

Fig. 6 Capture of test section evacuation.

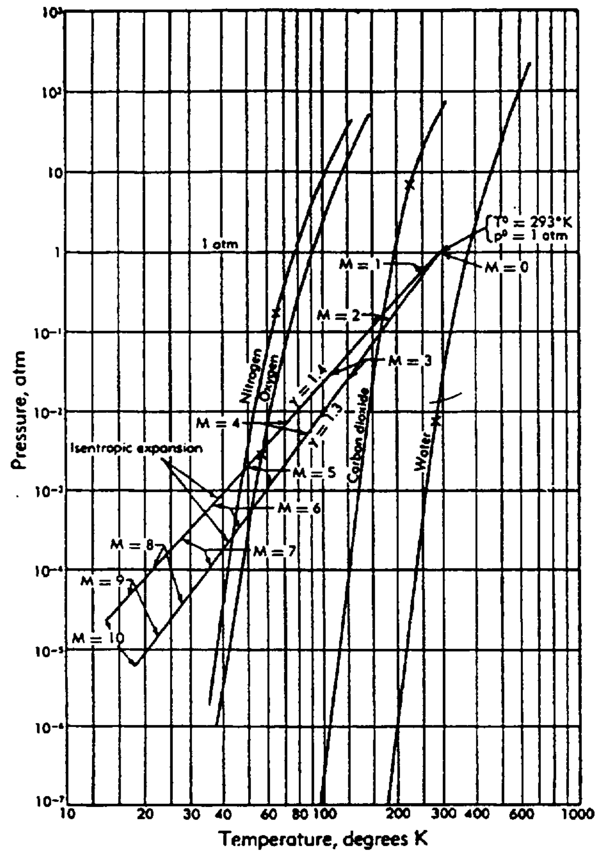

Fig. 7 Saturation lines for water, carbon dioxide, oxygen and nitrogen.

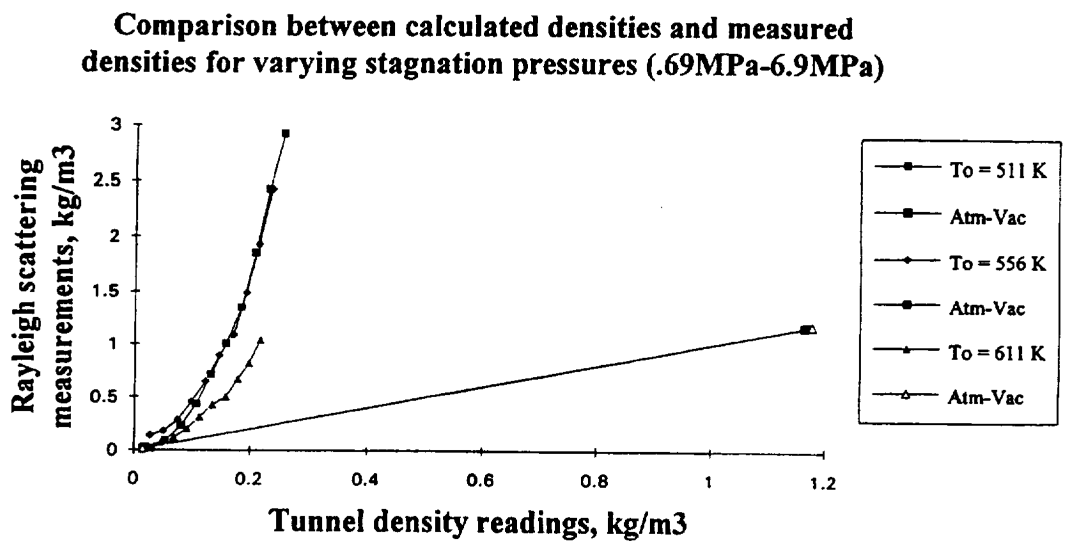

Fig. 8 Rayleigh scattering measurements during empty tunnel runs.

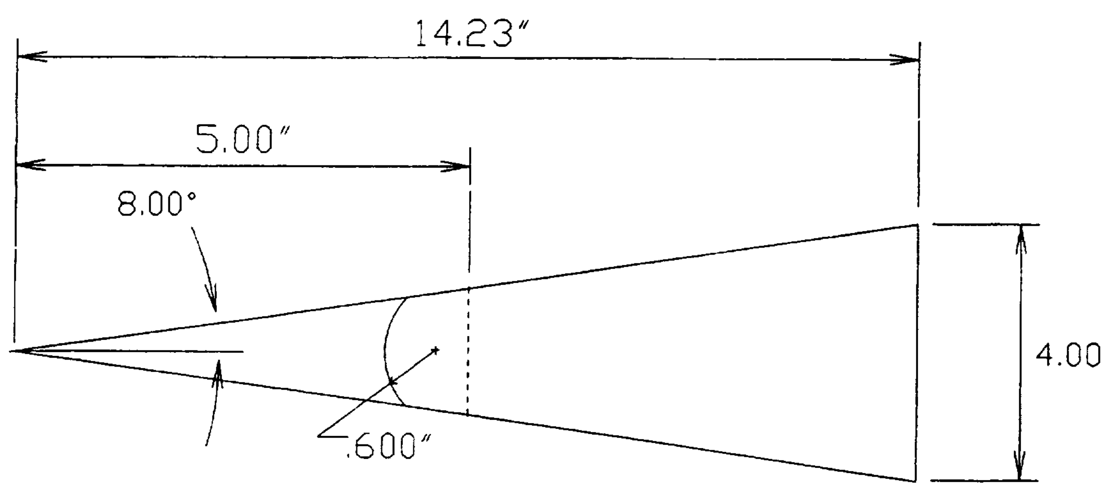

Fig. 9 Schematic of 8-degree half-angle blunt nose cone.

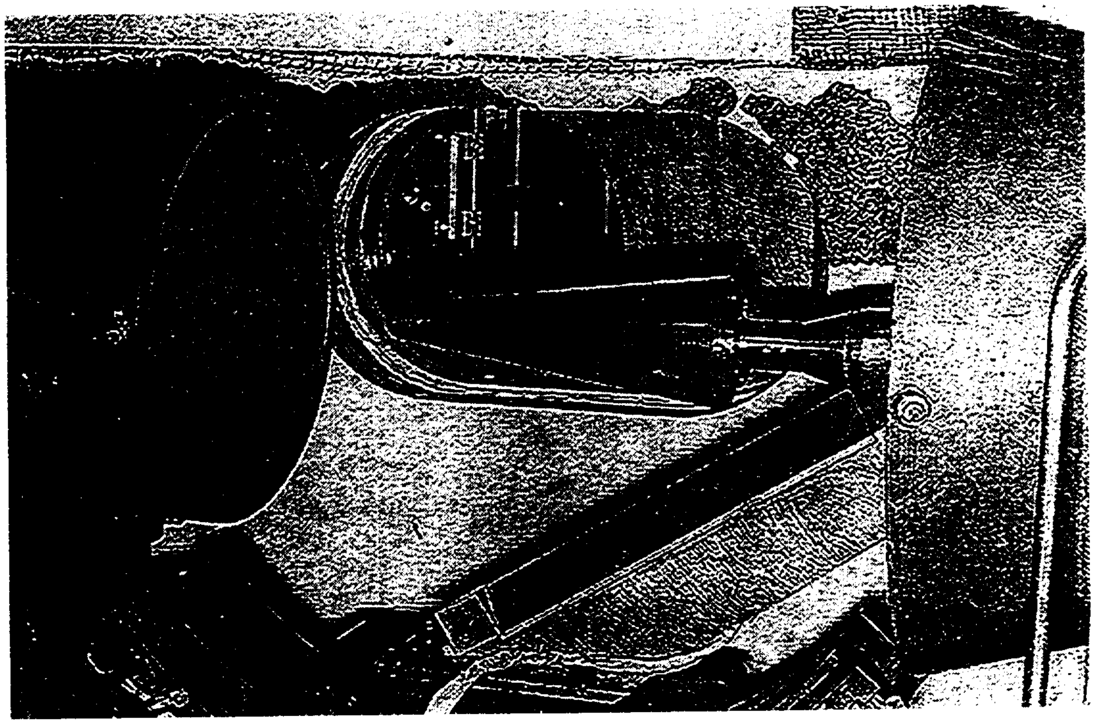

Fig. 10 8-degree half-angle blunt nose cone installed in Mach 6 wind tunnel.

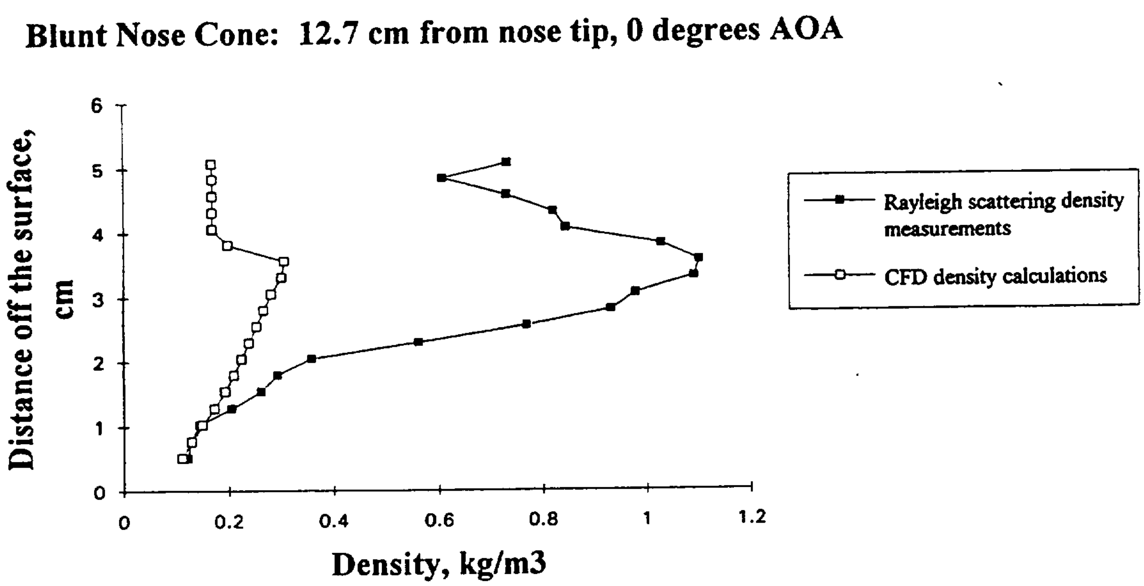

Fig. 11 Rayleigh scattering measurements and computational fluid dynamics comparison.